APRIL 27, 2020

U.S. DEPARTMENT OF ENERGY SMARTMOBILITY

Systems and Modeling for Accelerated Research in Transportation

MULTI-SCENARIO ASSESSMENT OF OPTIMIZATION OPPORTUNITIES DUE TO CONNECTIVITY AND AUTOMATION

Project ID# eems020

Pillar(s): CAVs

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OVERVIEW

Timeline

- Project start: October 1, 2016
- Project end: September 30, 2019
- Percent complete: 100%

Budget

- Total project funding: $1.077M
  - DOE share: 100%
  - Contractor share: 0%
- Funding for FY 2019
  - $381K

Barriers

- Accurate assessment of transportation system energy impacts of optimal coordination of connected and automated vehicles
- Availability of integrated tools, techniques, & core capabilities to understand & identify the most important levers to improve the energy productivity of future integrated mobility systems
- Determining the value and efficiency derived from new mobility technologies

Partners

- Project Lead: ORNL
- DOE SMART Mobility Lab Consortium
- Argonne National Laboratory➔ Vehicle models
- University of Delaware➔ Human-in-the-loop, small scale experimental data

RELEVANCE

- **Main challenge**: High uncertainty about energy impacts
  - Main focus in connectivity and automation research is safety
  - Considers mainly homogeneous traffic

- **Overall Objective**: Determine optimization opportunities to increase energy efficiency in full and partial CAV market penetration under diverse traffic scenarios
  - Expand framework to capture CAVs – human driver interactions under different traffic volumes
  - Analyze impacts when optimal coordination is applied considering different penetrations of CAVs

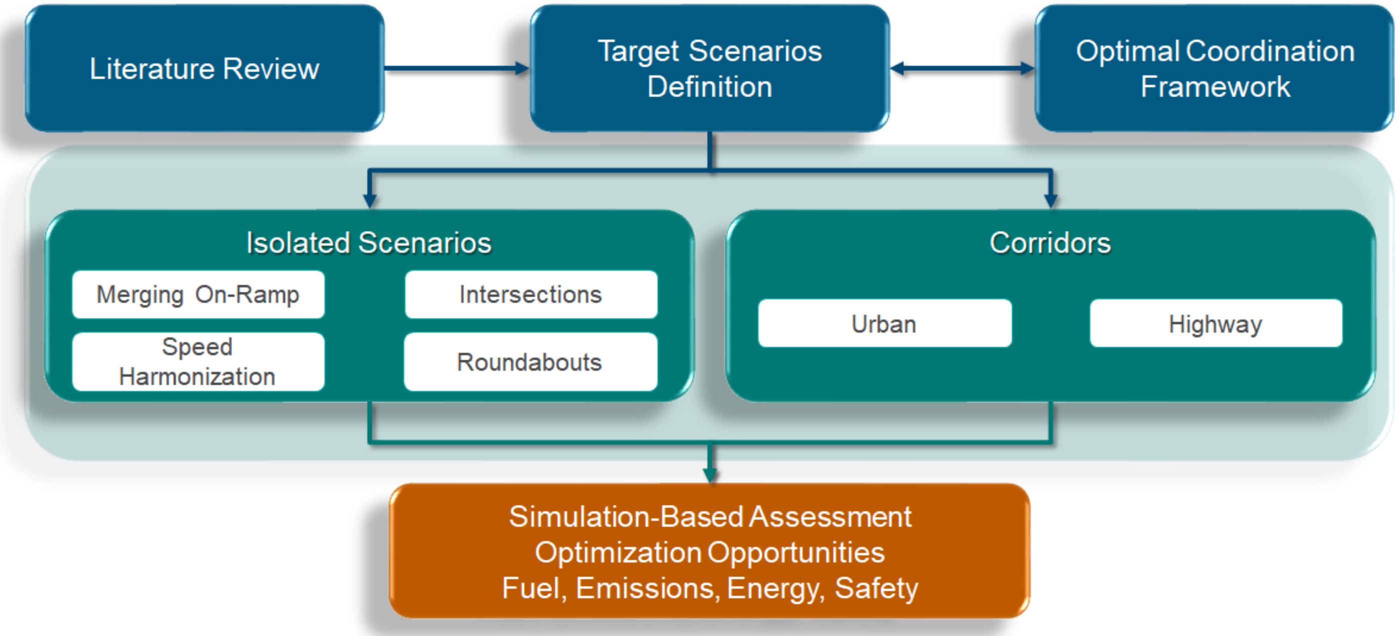
- **Relevance:**
  - Contribute to SMART Mobility program goal of yielding meaningful insights on how SMART technologies can improve Energy Productivity
  - Insights on efficient coordination strategies that can offer energy and mobility improvements considering heterogeneous fleets
  - Methodology to quantify the benefits of CAVs to inform public and private sector decision-making in deploying optimal vehicle coordination strategies to maximize mobility energy efficiency

MILESTONES

Task	Month / year	Status
1. Description of strategic lane change control for multilane scenarios	June 2019	Complete
2. Scaled testbed-based assessment of communication-related instabilities on the merging coordination	September 2019	Complete
3. Simulation-based assessment of energy implications for a real-world scenario	September 2019	Complete
4. Summary report	September 2019	Complete

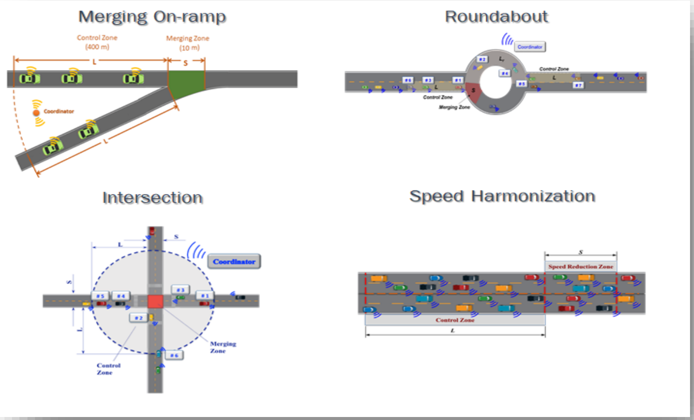
APPROACH

Overall Goal
Explore optimization opportunities to increase energy efficiency in full and partial CAV market penetration under diverse scenarios



APPROACH

- Literature Review*
- Optimal coordination framework
  - Based on optimal control
  - Closed-form solution
  - Feedback control
- Scenarios Definition
  - Bottleneck, Corridors



- Simulation
  - Traffic simulations
  - PTV VISSIM + MATLAB Integration
  - Traffic data for calibration (I75 corridor)
- Assessment
  - Fuel, energy, emissions estimation
    - Polynomial models
    - SMART Modeling Workflow fleet distribution scenarios (eems058)
  - Safety
    - Driving volatility
    - Time to collision

*Rios-Torres, J., and Malikopoulos, A.A., "A Survey on the Coordination of Connected and Automated Vehicles at Intersections and Merging at Highway On-Ramps," IEEE Trans. Intel. Trans. Syst., Vol. 18, 5, pp. 1066-1077, 2017

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APPROACH

FY17

Isolated scenarios
- 100% MPR
- Homogeneous Traffic

FY18

Interconnected scenarios
- Partial MPR
- Homogeneous-Heterogeneous

FY19

Real world scenarios
- Partial MPR
- Heterogeneous Traffic

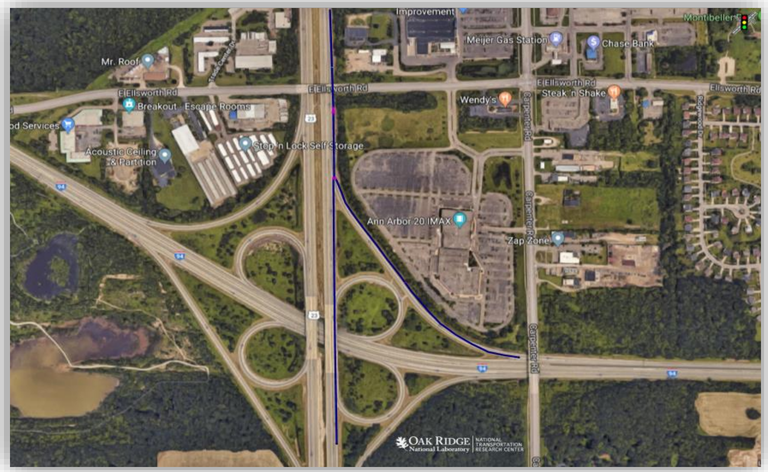
Optimal coordination: enabling smooth driving by controlling vehicles maneuvers at conflict zones

TECHNICAL ACCOMPLISHMENTS

COMPREHENSIVE EMISSIONS AND EFFICIENCY ANALYSIS

Single merge – Simulation Scenario Description

- Scenario based on the W I 94/N US 23 On-Ramp, Ann Arbor, Michigan
- Main road: 1 km
- Control zone length: 400 m
- Traffic flow Q= 2000 veh/h
- Main/ramp split: 60% / 40%



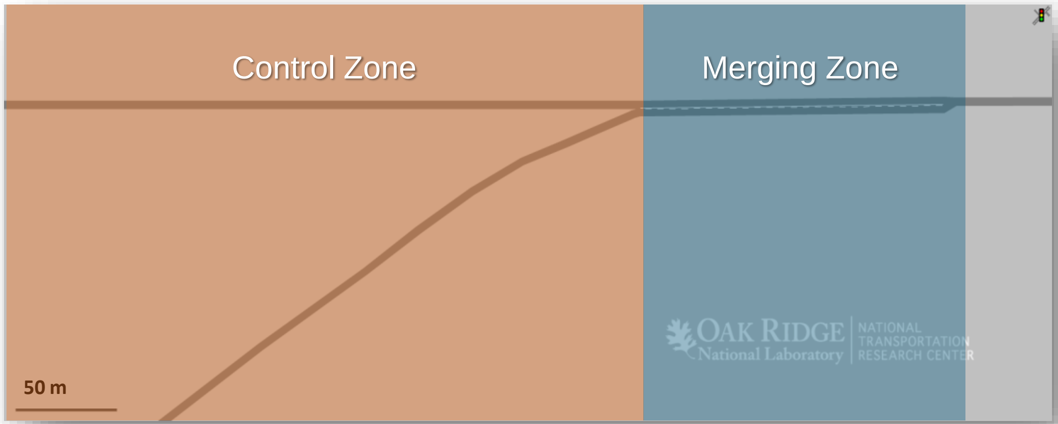
CAVs market penetration scenarios for simulation

	Baseline	2	3	4	5	6	7	8	9	10	11	12
% Light-duty CAVs	0	0	5	10	20	40	50	60	80	90	95	100
% Heavy-duty CAVs	0	100	100	100	100	100	100	100	100	100	100	100

COMPREHENSIVE EMISSIONS AND EFFICIENCY ANALYSIS

Single merge – Simulation Scenario Description

- **Heterogeneous traffic:**
  - **Light to heavy duty**
  - **Conventional, HEV, BEV, etc.**
  - **Fuel consumption and emissions models: SMART Modeling Workflow (eems058)**
- **Baseline: human drivers - Wiedemann car following model**
- **12 Market penetration rates (MPRs)**



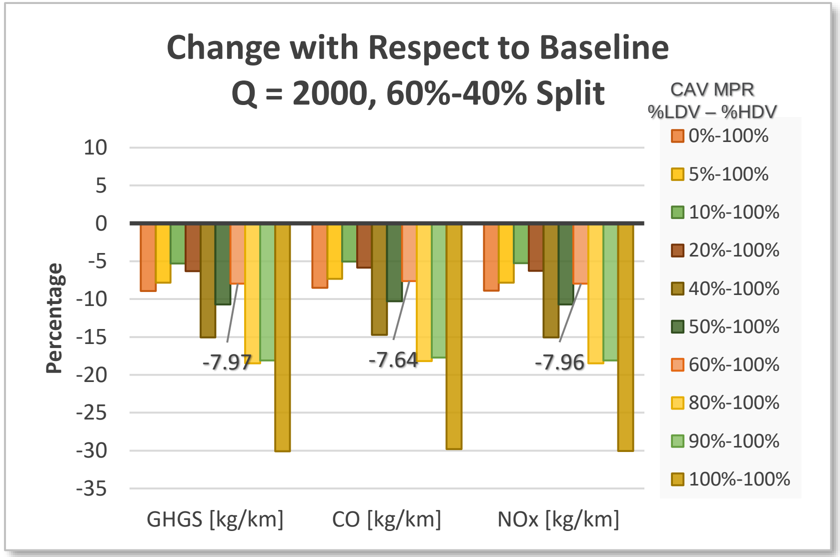
CAVs market penetration scenarios for simulation

	Baseline	2	3	4	5	6	7	8	9	10	11	12
% Light-duty CAVs	0	0	5	10	20	40	50	60	80	90	95	100
% Heavy-duty CAVs	0	100	100	100	100	100	100	100	100	100	100	100

MERGING COORDINATION HAS POTENTIAL FOR SIGNIFICANT EMISSIONS REDUCTION

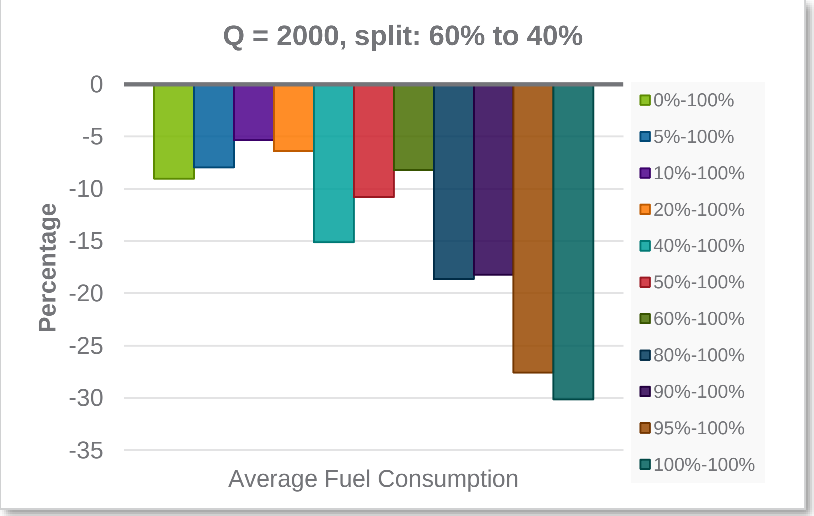
Single Merge - Results

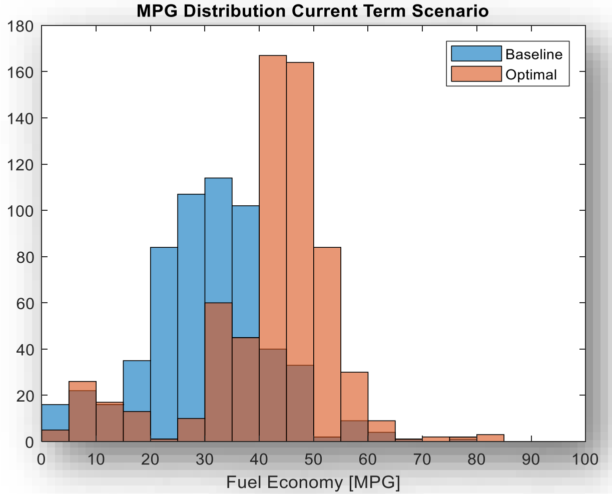
- Emissions reduction sensitive to MPR
- Higher variability at lower MPR
- Similar trend for all other emissions estimated: VOC, PM10, PM2p5, Sox, BC, POC, CH4. NO2



MERGING COORDINATION SIGNIFICANTLY REDUCE FUEL CONSUMPTION

Single Merge - Results





With partial penetration of CAVs and considering a heterogeneous fleet, the optimal coordination framework can provide 3% to 30% fuel savings under moderate to heavy traffic

COMPREHENSIVE EFFICIENCY AND EMISSIONS ANALYSIS

I75 Corridor

- Scenario based on the I75 Corridor in Tennessee
- Corridor length: 6.9 miles
- # on-ramps: 2
- # off-ramps: 2
- Traffic flow: 2000 veh/h split: 60% to 40%
- Simulated 8 Market penetration rates (MPRs)

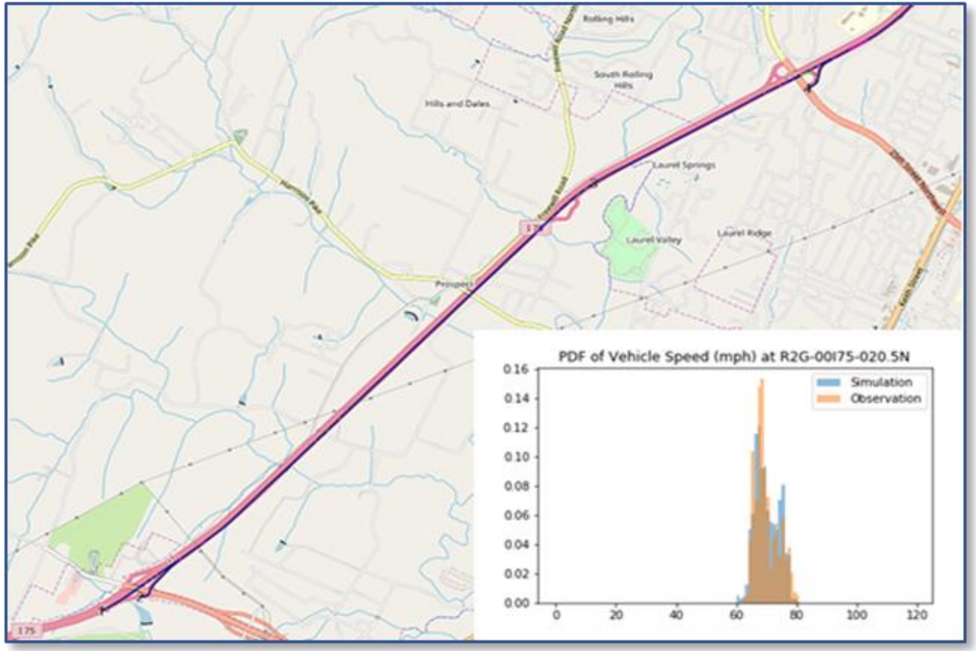
CAVs market penetration scenarios for simulation

	Baseline	2	3	4	5	6	7	8
% Light-duty CAVs	0	0	5	10	20	50	80	100
% Heavy-duty CAVs	0	100	100	100	100	100	100	100

COMPREHENSIVE EFFICIENCY AND EMISSIONS ANALYSIS

I-75 Corridor

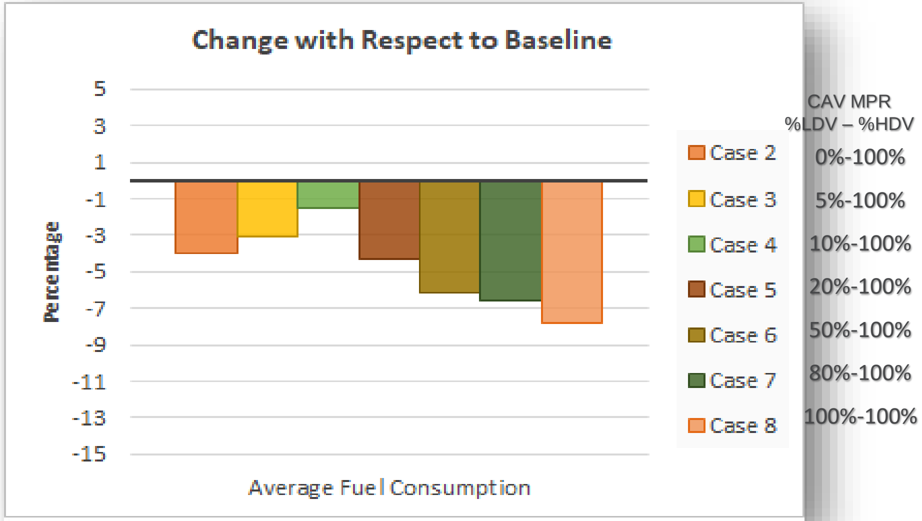
- Heterogeneous traffic:
  - Light to heavy duty
  - Conventional, HEV, BEV, etc.
  - % electrified vehicles: <2%
  - Fuel consumption and emissions models: SMART Modeling Workflow (eems058)
- Baseline: human drivers - Wiedemann car following model
- 8 Market penetration rates (MPRs)



EFFICIENCY BENEFITS IN A CORRIDOR ARE ACHIEVED WITH A MODEST MARKET SHARE OF CAVS

I-75 Corridor

- 20% CAVs MPR ➔ over a 4% reduction in fuel consumption
- 100% CAVs MPR ➔ over a 7% reduction in fuel consumption
- >10% CAVs MPR ➔ steady increase in fuel savings
- Results sensitive to MPR
- Higher variability at low MPR



If strategies to optimize the vehicle when driving outside of the merge zone are applied, the benefits will be higher

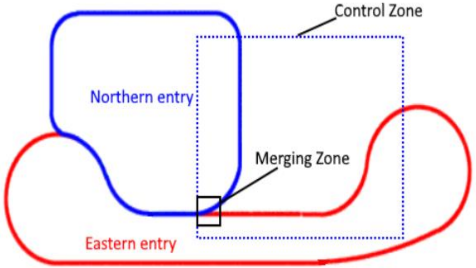
UNDERSTANDING UNCERTAINTY IN THE SCHEDULING OF CAVS

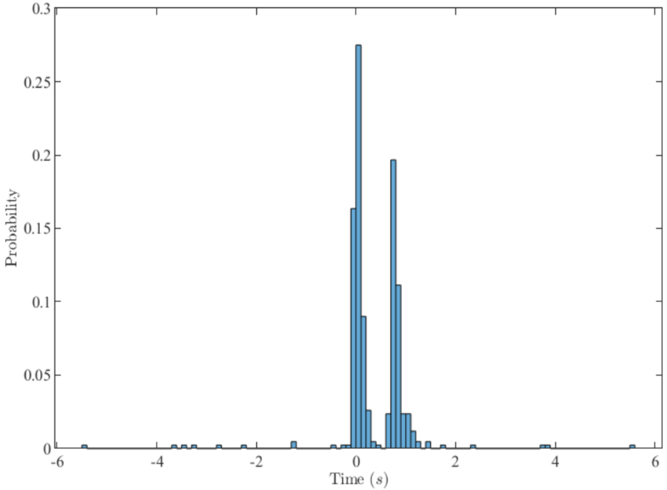
- Experiments conducted at University of Delaware Scaled Smart City (UDSSC)
  - Fully integrated smart city
  - Allows evaluation of control and learning algorithms and applicability in hardware
  - Uses high-end computers
  - Uses a VICON motion capture system
  - Up to 35 scaled CAVs (Raspberry Pi 3B with a 1.2 GHz quad-core ARM processor)
  - Main frame computer: processor: Intel Core i7 − 6950X CPU @ 3.00 GHz x 20, Memory: 125.8 Gb.

  UDSSC has been used successfully for coordination of CAVs and implementation of reinforcement learning policies.

UNDERSTANDING UNCERTAINTY IN THE SCHEDULING OF CAVS

- A random number of CAVs between 4 and 6 is assigned for each north and east entries
- Number of experiments: 44
- Scheduling based in FIFO System
- Error mainly distributed around 0





Maximum	Mean	Median	Minimum	Standard Deviation	Variance	Count
5.53	0.34	0.124	-5.46	0.73	0.53	422

RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS (1)

The reviewer stated that a main objective of the work is to assess the energy savings potential of CAV technology deployment; however, the important effect of vehicle auxiliary loads from CAV technologies has been neglected. It sounds like future work is intended to address this, but it was not clear to the reviewer that the importance of increased auxiliary loads was fully understood.

- **Actions Taken:**
  - We used higher fidelity vehicle models provided by the ANL team (eems058)
  - The models consider
    - Assumptions regarding energy consumption due to sensors and computation
    - Heterogeneous fleets and different distributions of vehicle makes and models according to a predefined current time scenario

RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS (2)

- **The reviewer had two comments. The first concerned why the entrance ramp is prioritized for study. The reviewer agreed that it presents as a safety case to be solved, but did not expect that there is a large amount of fuel to be saved relative to other traffic use cases, such as work zone slowdowns, etc. The second comment was that the reviewer thought that there needed to be more traffic scenario studies.**

- **Response:**
  - The developed framework can be adapted to the case of work zones
  - As the project ended last September, future work can be devoted to study other traffic scenarios in more detail.

COLLABORATIONS

Vehicle models

HIL Validation

Subcontractor, human-in-the-loop, small scale experimental data for validation

Non-funded collaboration – safety

REMAINING CHALLENGES AND BARRIERS

- Diversity in actual traffic scenarios
  – Need to represent drivers' diversity (powertrain types, driver diversity, etc)

- Calibration for additional traffic scenarios
  – Real traffic data is limited

- Simulation
  – Comprehensive simulation assessment is computationally and time intensive

PROPOSED FUTURE RESEARCH BEYOND THIS PROJECT

- Scheduling optimization
- Further characterization of communications instabilities
- Analysis of additional traffic scenarios
- Analysis considering future fleet distribution scenarios
- Considering diversity in terms of human driver behaviors

Any proposed future work is subject to change based on funding levels

SUMMARY SLIDE

- **Approach:**
  - Develop optimal CAVs coordination algorithms based on optimal control and adaptable to multiple traffic scenarios.
  - Generate methodology to assess the benefits to inform public and private sector decision-making in deploying optimal vehicle coordination strategies to maximize mobility efficiency
- **Technical Accomplishments:**
  - Demonstrated the effectiveness of the controller to improve fuel economy on a traffic corridor under different MPR of CAVs
  - Results revealed that 20% MPR of CAVs can deliver over 4% fuel savings in a highway corridor with two on-ramps. At 100% MPR over 7% fuel savings are achieved
- **Future Work:**
  - Exploring impacts of optimal coordination framework in additional traffic scenarios (including work zones, speed reduction zones, intersections, urban and highway corridors, etc.) with consideration of further agent diversity and different market penetration rates

Any proposed future work is subject to change based on funding levels

THANKS! / GRACIAS!
QUESTIONS?

Team:

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MOBILITY FOR OPPORTUNITY

FOR MORE INFORMATION

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Technical Back Up Slides

OPTIMAL COORDINATION FRAMEWORK BASICS

Optimal Control Problem

$$\min_{u_i} J = \min_{u_i} \frac{1}{2} \int_{t_i^o}^{t_i^f} u_i^2 \, dt$$

We aim to minimize each vehicle's acceleration in the control zone and coordinate their access to the merging zone to avoid conflicts

subject to

$$\left.\begin{aligned} \dot{p}_i(t) &= v_i(t) \\ \dot{v}_i(t) &= u_i(t), \end{aligned}\right\} \text{Vehicle Dynamics}$$

$$\left.\begin{aligned} &\dot{p}_i(t_i^0) = 0, \\ &\dot{v}_i(t_i^0) \text{ given,} \\ &\dot{p}_i(t_i^f) \text{ given} \\ &\dot{v}_i(t_i^f) \text{ given} \end{aligned}\right\} \text{Boundary Conditions}$$

- A closed form-solution is found through Hamiltonian Analysis
- The solution is applied in receding horizon, i.e., it is computed and updated at each sample time of the simulation
- Minimizing acceleration translates into fuel/energy reduction but might not take fully advantage of the regeneration capabilities of electrified powertrains
- t_f is defined to schedule the arrival of CAVs at the merging zone

* ***J. Rios-Torres*** and A. A. Malikopoulos, "Automated and Cooperative Vehicle Merging at Highway On-Ramps," in IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 4, pp. 780-789, April 2017. doi: 10.1109/TITS.2016.2587582